AD-A227 816

# REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704 0188

DTIC ELECTE OCT 05 1990 S B D

| | |
|---|---|
| 1a REPORT SECURITY CLASSIFICATION (U) | 1b RESTRICTIVE MARKINGS NA |
| 2a SECURITY CLASSIFICATION AUTHORITY NA | 3 DISTRIBUTION/AVAILABILITY OF REPORT Unlimited |
| 2b DECLASSIFICATION/DOWNGRADING SCHEDULE NA | |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S) NA | 5 MONITORING ORGANIZATION REPORT NUMBER(S) NA |
| 6a NAME OF PERFORMING ORGANIZATION The University of Texas at Dallas; 6b OFFICE SYMBOL (If applicable) NA | 7a NAME OF MONITORING ORGANIZATION Office of Naval Research |
| 6c ADDRESS (City, State, and ZIP Code) Center for Applied Optics, Richardson, TX 75083-0688 | 7b ADDRESS (City, State, and ZIP Code) Ballston Tower #1, 800 North Quincy Street, Arlington, VA 22217-5000 |
| 8a NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research; 8b OFFICE SYMBOL (If applicable) 1112LO | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-86-K-0452 |
| 8c ADDRESS (City, State, and ZIP Code) Ballston Tower #1, 800 North Quincy Street, Arlington, TX 22217-5000 | 10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 61153N; PROJECT NO R&T 412j012---03; TASK NO -; WORK UNIT ACCESSION NO - |

11 TITLE (Include Security Classification)
Theoretical Studies of Squeezed-State Generation in Propagating Laser Beams

12 PERSONAL AUTHOR(S)
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| 13a TYPE OF REPORT | 13b TIME COVERED | 14 DATE OF REPORT (Year, Month, Day) | 15 PAGE COUNT |
|---|---|---|---|
| Final | FROM ____ TO ____ | 1990 September 28 | 5 |

16 SUPPLEMENTARY NOTATION

| 17 COSATI CODES | | | 18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |
|---|---|---|---|
| FIELD | GROUP | SUB-GROUP | Squeezed states of light |
| - | NA - | | Laser-pulse propagation |

19 ABSTRACT (Continue on reverse if necessary and identify by block number)


This research investigated the feasibility of generating squeezed states of light using the conical emission that occurs when a nearly resonant laser beam propagates in an atomic vapor. Preliminary results indicate that a high degree of squeezing may be obtained in pulses. Methods were developed for the inclusion of diffraction and transverse effects.


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| 20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21 ABSTRACT SECURITY CLASSIFICATION (U) |
| 22a NAME OF RESPONSIBLE INDIVIDUAL Dr. Herschel S. Pilloff | 22b TELEPHONE (Include Area Code) 202-696-4223; 22c OFFICE SYMBOL 1112LO |

DD Form 1473, JUN 86 Previous editions are obsolete SECURITY CLASSIFICATION OF THIS PAGE

S/N 0102-LF-014-6603

DISTRIBUTION STATEMENT A
Approved for public release; Distribution Unlimited

FINAL TECHNICAL REPORT

# Theoretical Studies of Squeezed-State Generation in Propagating Laser Beams

U.S. Office of Naval Research
Contract No. N00014-K-86-0452

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28 September 1990

## SUMMARY OF WORK ACCOMPLISHED

*Contract Description*

The purpose of this research was to investigate the feasibility of generating squeezed states of light using the conical emission that occurs when a nearly resonant laser beam propagates in an atomic vapor. The guiding idea was that if phase-sensitive nonlinear-optical processes contribute to the development of conical emission, then one should expect the variance of the field operator corresponding to the conical emission to be altered in the same way as has been observed for four-wave mixing in other media.

*Scientific Problem*

The key steps in this research were:

(1) Development of a computer program that *accurately* describes the propagation of a beam of light through a vapor of two-level atoms, taking diffraction and the transverse profile of the beam into account. For the purposes of this research, it was essential to avoid making use of the modal descriptions (which use one field for each frequency or direction of propagation) usually employed in analytical studies. In our approach[1] all information about new frequencies or new directions of propagation arising as a result of the interaction between the laser beam and the atomic medium is carried by a single, numerically calculated field.

(2) Investigation of the origins of conical emission.

Harter and Boyd suggested that conical emission is the result of noncollinearly-phase-matched four-wave mixing involving the incident beam and the upper and

[1] M. E. Crenshaw and C. D. Cantrell, "Temporal and Spatial Modulation in Laser-Pulse Propagation", Optics Letters 13, 386-388 (1988).

lower Rabi sidebands.[2] Whether conical emission is generated by a phase-sensitive nonlinear process will determine whether the squeezed states can be generated as the result of propagation.

(3) Derivation of the Langevin equations for the propagating field and the atomic medium.

(4) Derivation and numerical implementation of a Lyapunov equation for the variance of the propagating field.

(5) Investigation of the possibility of generating squeezed conical emission using the results of steps (2) and (4).

*Scientific and Technical Approach*

The approach by which the scientific issues listed above were addressed is as follows:

(1) In keeping with the scientific principle of studying the effect of one variable at a time, we began our research by studying the propagation of a classical electromagnetic field through a dilute, collisionless atomic vapor. The paraxial wave equation was approximated in a way that lends itself to numerical computation, and a method was found to solve the time-dependent Schrödinger equation with unprecedented accuracy. The paraxial wave equation can be attacked with finite-difference, finite-element or spectral methods. For the sake of computational speed we assumed that the laser beam is cylindrically symmetric. Since spectral methods lend themselves well to vectorization, we chose to use a spectral method.[3] The problem of finding a numerical method for the time-dependent Schrödinger equation was attacked using the method of Chebyshev approximation to find an initial method of high accuracy, and subsequently searching a multidimensional parameter space to find the best method.

(2) If four-wave mixing involving the upper and lower Rabi sidebands plays a role in the development of conical emission, then one would expect to see new propagating waves with the same transverse wave vector (because of noncollinear phase matching) at the Rabi sideband frequencies. The existence of such waves can conveniently be investigated using the spatial and temporal Fourier transform of the transmitted field.

(3) The Langevin equations for the propagating field were derived using the approach of W. H. Louisell, *Quantum Statistical Properties of Radiation,* Chapters 6-7.

*Results*

We obtained the following results:

(1) We wrote and debugged a computer program using a vectorizable Hankel transform, which converts the paraxial wave equation into an ordinary differential equation.[4] We developed and debugged an algorithm for the accurate solution of

[2] D. J. Harter and R. W. Boyd, Phys. Rev. A 29, 739 (1984).

[3] B. J. Coffey, M. Lax, and C. J. Elliot, IEEE J. Quant. Elect. **QE-19**, 297 (1983).

[4] M. E. Crenshaw, C. D. Cantrell, D. D. Chu and C. A. Glosson, "Laser Propagation in Atomic Vapors", in *Science and Engineering on Cray Supercomputers*, edited by John E. Aldag (Minneapolis, Cray Research, Inc., 1987), pp. 477-490.

the time-dependent Schrödinger equation, and incorporated this algorithm into the calculation of the polarization source term in the paraxial wave equation. We believe that the resulting computer program is the most powerful and accurate tool ever developed for research on near-resonance nonlinear processes involving a propagating laser beam.

(2) We showed that conical emission can be the result of the breakup of a laser pulse into solitary waves.[5] For an incident pulse with a transverse as well as a temporal profile, the crests and troughs of the two- or three-dimensional solitary waves are curved in a time-radius plane. The temporal modulation associated with pulse breakup appears as Rabi sidebands in the spectrum, while the curvature of the solitary waves in the time-radius plane results in a transverse spatial modulation that leads to conical emission in the far field. These results were obtained by performing detailed numerical calculations of the time-dependent paraxial propagation of a cylindrically symmetric laser pulse through a vapor of two-level atoms under the rotating-wave and slowly-varying envelope approximations in the limit of no collisional damping or Doppler broadening.[6] Our results can be interpreted readily in terms of optical nutation on the Bloch sphere and in terms of noncollinear phase matching through the curvature of the solitary waves rather than through additional parametrically generated waves.[7] We found that self-focusing is not required for the generation of conical emission, although it would be difficult to separate these effects experimentally.

(3) We derived two completely new approximations for the damped response of a two-level system to a time-dependent electromagnetic field.[8] Comparison with numerical solutions of the full density-matrix equations of motion demonstrated that the new approximations significantly improve upon the collisional steady-state approximation (including the often-used method of "adiabatic elimination of atomic variables") and the adiabatic-following approximation.

(4) We showed that atomic motion does not affect the conclusions already mentioned under (2) above by performing computations including the longitudinal Doppler effect for the same cases studied by Crenshaw and Cantrell using a completely different numerical method.[9] This work also serves as a check on the correctness of the computations performed by Crenshaw and Cantrell.

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[5] M. E. Crenshaw and C. D. Cantrell, "Conical emission as a result of pulse breakup into solitary waves", Physical Review A 39, 126-148 (1989).

[6] M. E. Crenshaw, "Coherent Sideband Generation and Conical Emission as a Result of Pulse Breakup into Solitary Waves" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 11, 14 June 1989.

[7] M. E. Crenshaw and C. D. Cantrell, "Rabi oscillations in an infinite-order correction to the adiabatic approximation for a two-level system", Physical Review A 37, 3338-3350 (1988).

[8] M. E. Crenshaw and C. D. Cantrell, "Time-dependent collisional approximations for two-level systems", Physical Review A 39, 5705-5716 (1989).

[9] Nasser Danesh, "Effects of Atomic Motion on Breakup and Propagation of Quasiresonant Laser Pulses" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 17, 22 September 1989.

(5) It is well known that as the result of the quantum-classical correspondence (which is discussed in Louisell's book), it is possible to perform computations of the quantum statistics of the electromagnetic field by solving differential equations for ordinary functions instead of operator differential equations. In this approach the classical function associated with a quantum-mechanical operator obeys a classical Langevin equation with a noise source. We showed that performing propagation calculations with direct simulation of noise, that is, with a time-correlated pseudorandom noise input, requires an inordinate computational effort. We developed a method for generating time-correlated Gaussian noise using autoregression sequences[10] which is very fast and is computationally stable.

(6) We derived a vector c-number Langevin equation for a single propagating mode of the field, and have generalized the result from one to many modes. By considering the special case of a quadratic nonlinearity, we showed that the nonlinear diffusion matrix may be non-positive-definite.[11]

(7) We derived and implemented numerically a Lyapunov equation for the variance of a single mode of the field.[12] An analysis of analytical and numerical solutions for various pump pulse shapes yields information about the production and properties of squeezing. These results give important guidance as to the conditions under which squeezing can be produced, as well as details of the squeezing produced by a pulsed pump.

The computer programs we created for laser-pulse propagation are applicable to experiments with sufficiently short pulses. Although we laid most of the groundwork for studying more general cases including collisions, atomic motion and quantum-statistical effects, these effects could not be integrated into the laser-pulse propagation program before the end of the contract.

*Special Significance of Results*

The problem of finding a physically satisfying explanation for conical emission is nearly two decades old. We believe that our results are the first theoretical results in this area that are solidly based on fundamental physics and that are free of crippling approximations.

*Unique Aspects*

This is probably one of the largest and most ambitious computational projects ever undertaken in the field of quantum optics. We used over 2000 CPU *hours* of Cray X-MP/24 time and roughly ten times that amout of Convex CPU time. The availability of two Convex computers at UTD and a Cray XMP/24 at the University of Texas System Center for High Performance Computing (as part of cost sharing with the Office of Naval Research) constituted a uniquely valuable form of support for this

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[10] N. R. Davis, "Correlated Noise Generation Using Autoregression Sequences", UTD Center for Applied Optics Technical Report No. 3, September 1987.

[11] N. R. Davis and C. D. Cantrell, "Squeezed states in the context of Langevin equations and non-positive-definite diffusion coefficients", Journal of the Optical Society of America B 6, 74-81 (1989).

[12] N. R. Davis, "A Langevin Approach to Squeezed States of Light" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 13, 20 June 1989 (unpublished).

and other research.

## LIST OF TECHNICAL REPORTS

1. Nolan R. Davis, "Correlated Noise Generation Using Autoregression Sequences", UTD Center for Applied Optics Technical Report No. 3, September 1987.
2. Michael Evan Crenshaw, "Coherent Sideband Generation and Conical Emission as a Result of Pulse Breakup into Solitary Waves" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 11, 14 June 1989.
3. Nolan Ray Davis, "A Langevin Approach to Squeezed States of Light" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 13, 20 June 1989.
4. Nasser Danesh, "Effects of Atomic Motion on Breakup and Propagation of Quasiresonant Laser Pulses" (Ph.D. Thesis), UTD Center for Applied Optics Technical Report No. 17, 22 September 1989.

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1. M. E. Crenshaw, C. D. Cantrell, D. D. Chu and C. A. Glosson, "Laser Propagation in Atomic Vapors", in *Science and Engineering on Cray Supercomputers,* edited by John E. Aldag (Minneapolis, Cray Research, Inc., 1987), pp. 477-490.
2. M. E. Crenshaw and C. D. Cantrell, "Rabi oscillations in an infinite-order correction to the adiabatic approximation for a two-level system", Physical Review A **37**, 3338-3350 (1988).
3. M. E. Crenshaw and C. D. Cantrell, "Temporal and spatial modulation in laser-pulse propagation", Optics Letters **13**, 386-388 (1988).
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5. N. R. Davis and C. D. Cantrell, "Squeezed states in the context of Langevin equations and non-positive-definite diffusion coefficients", Journal of the Optical Society of America B **6**, 74-81 (1989).
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